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MEMORANDUM FOR PRR (~~Contractor~~/In-House Publication)

1 June 1999

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SUBJECT: Authorization for Release of Technical Information, Control Number: AFRL-PR-ED-TP-FY99-0098
Moszee, "Liquid Rocket Propulsion – Evolution and Advancements: Rocket-Based Combined Cycle"
AIAA (Public Release)

Liquid Rocket Propulsion –
Evolution and Advancements

Rocket-Based Combined Cycle

Dr. Ray Moszée

Air Force Research Laboratory
Edwards AFB, CA

June 25, 1999

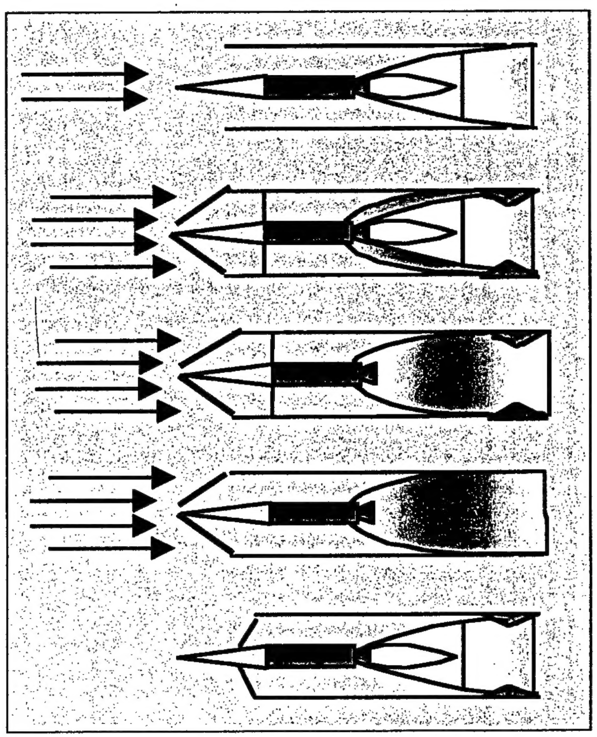
Outline

- Background
- History of RBCC
- Integrated Performance Analysis
- Current Activities
- Future Prospects

Cycle Benefits

- **Engine performance covers a broad operating range**
  - **Hypersonic vehicle mission application**
- **Benefits derived from *Airbreathing Propulsion***
  - **High specific impulse**
  - **Low vehicle gross weight**
- **Benefits derived from *Rocket Propulsion***
  - **High thrust (acceleration)**
  - **High energy density**
  - **Design experience**
- **Optimum performance is achieved by combined cycle approach**
  - **Synergistically blends rocket and ram/scramjet propulsion technology**
  - **Vehicle designer's options are broadened considerably**

RBCC Engine Operating Modes



Ducted Rocket
Low Speeds
Mach 0 to 1.5

Rocket Ramjet
Low Mach Numbers
Mach 1.5 to 3

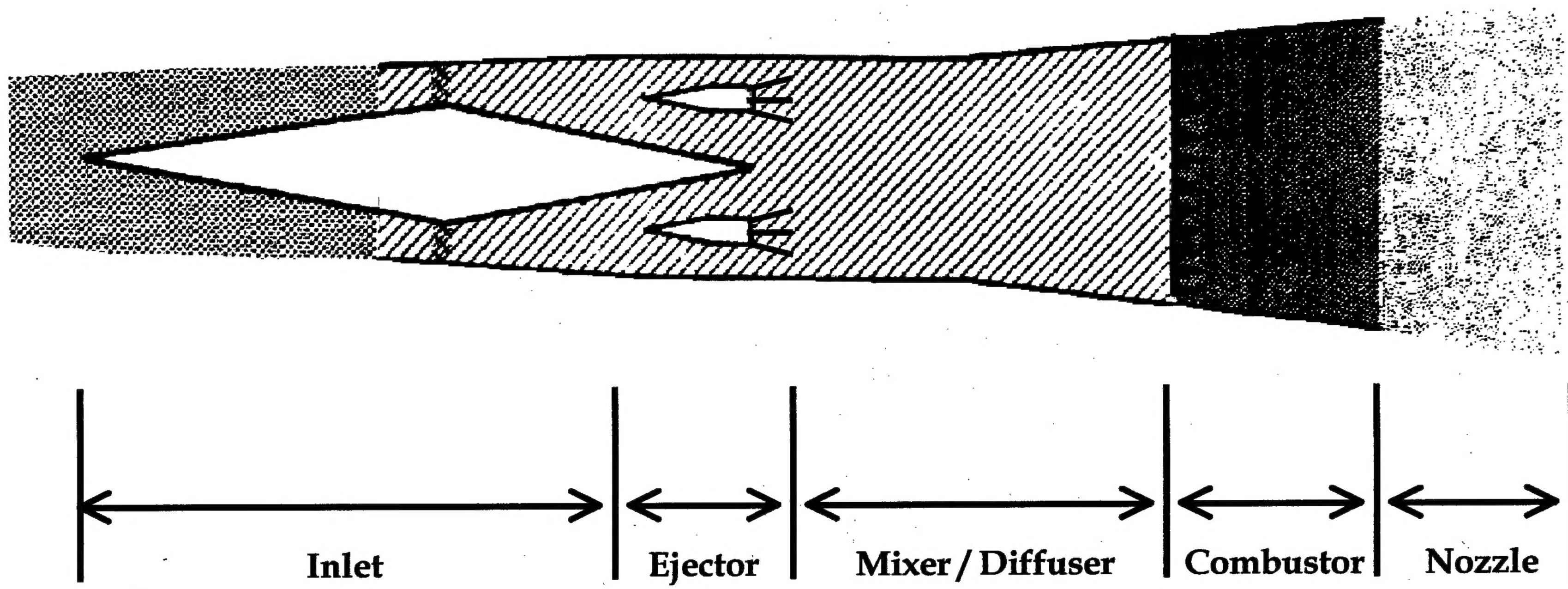
Ramjet
Mach 3 to 5

Scramjet
Mach 5 to 10

Rocket
Mach > 10 and/or
High Altitude

- **Bridges air and space more than any propulsion concept**
- **Enables low cost DoD and commercial space launch systems**
- **Provides trans-atmospheric vehicle capability enabling many new missions**

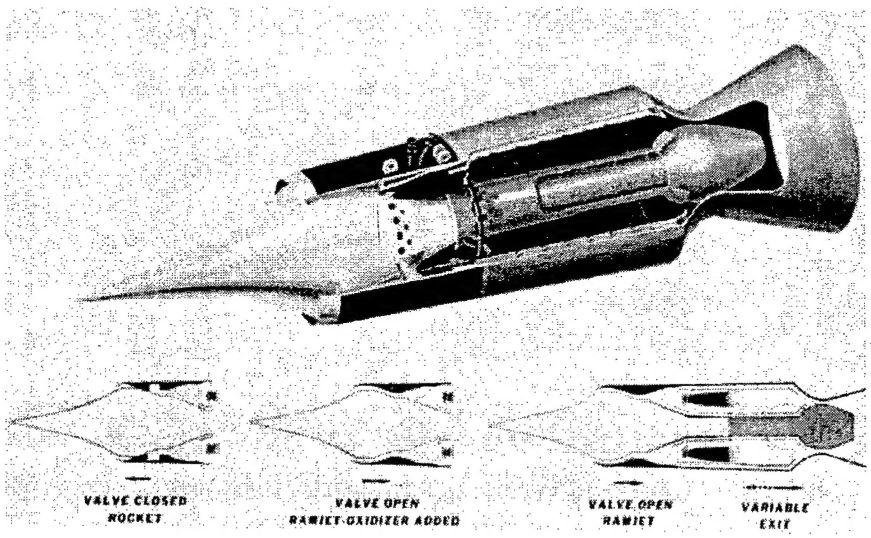
RBCC Engine Description



RBCC History

- RBCC engine is <u>not</u> a new propulsion cycle
  - Significant work has been accomplished back in the 60's
- Engine cycle experienced a rebirth in the 90's
  - Military applications
  - Commercial applications
- Performance and structural challenges of the past will hopefully be solved by incorporating recent technology advancements
  - Improved specific impulse
  - Higher engine thrust-to-weight
  - Efficient thermal management
- Opportunities exist for joint government / industry investments

Hyperjet



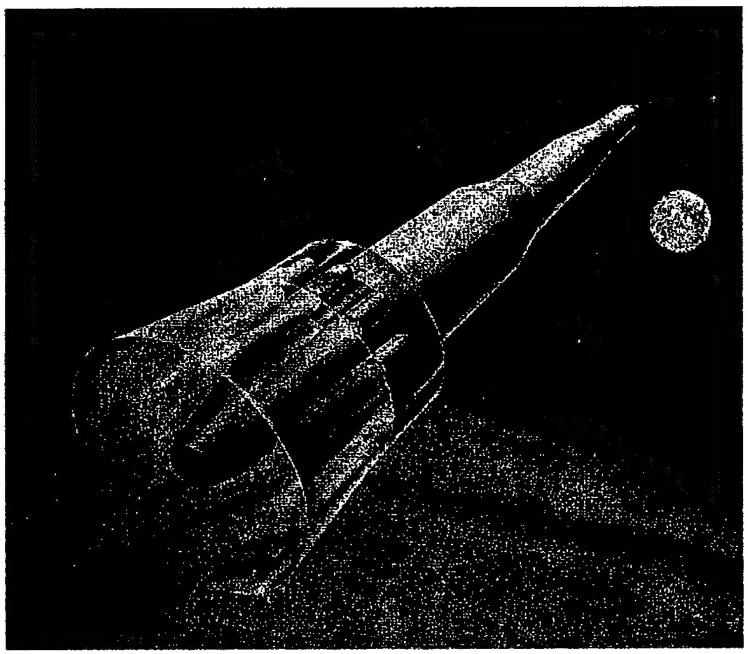
Dual-Mode Rocket/Ramjet Engine (1958)
Reached the Flight Demonstration Stage

Rocket Mode Launch

[redacted]

The First RBCC Engine Tested

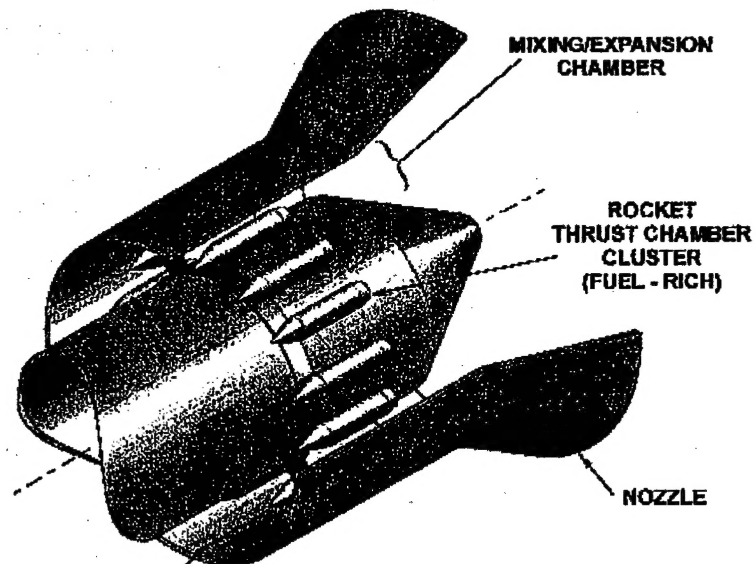
Rocket Engine Nozzle Ejector (RENE)



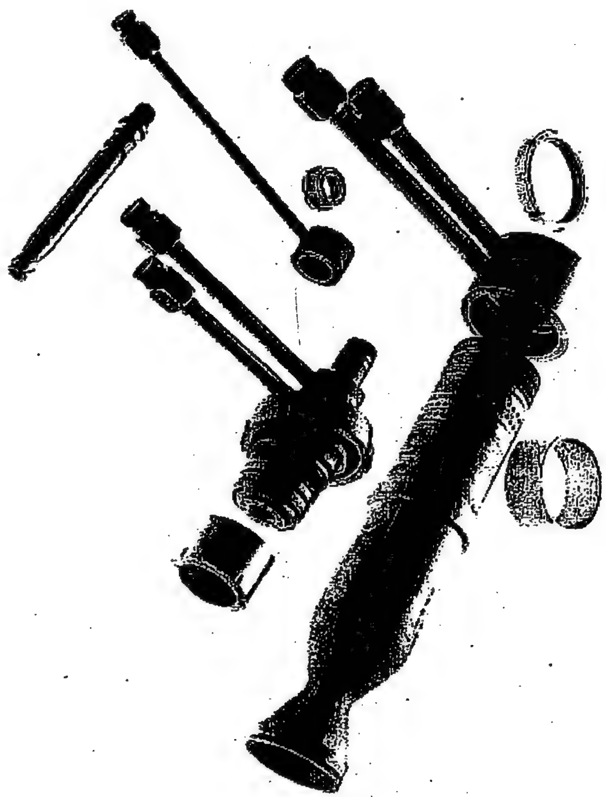
Air-Augmented Rocket Powered Multistage Vehicle

RENE Propulsion System (1960)

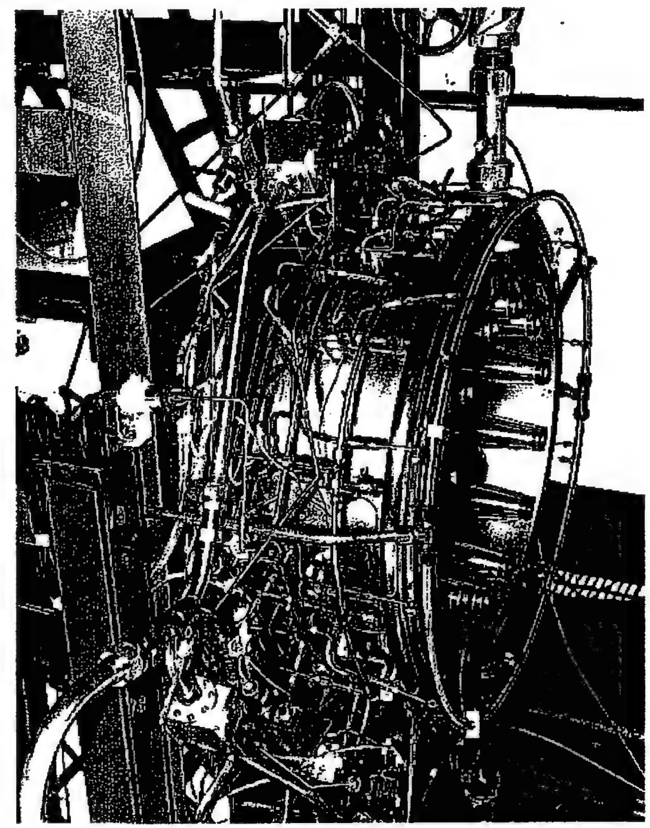
SIMPLE AIR-AUGMENTED ROCKET
(e.g., RENE-ROCKET ENGINE NOZZLE EJECTOR)



Rocket Engine Nozzle Ejector (RENE)

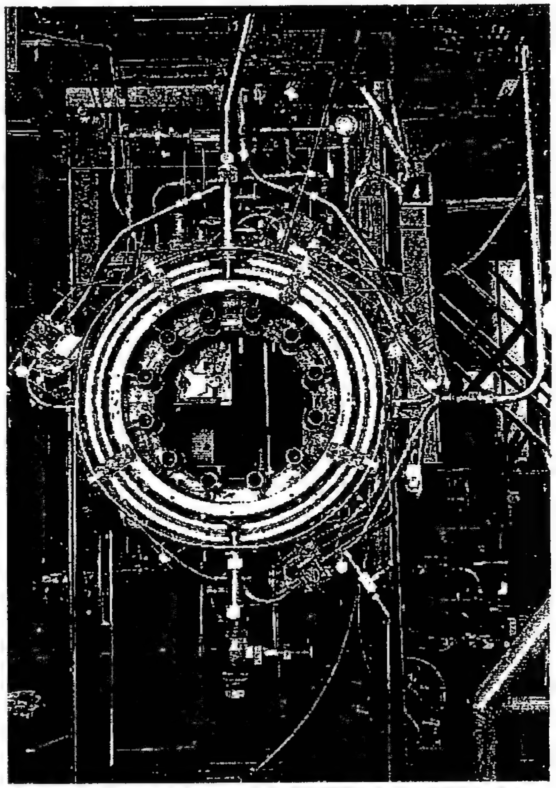


Detailed Hardware View of the LO_2 / RP-1 Water-Cooled Thrust Chamber Assembly Used in the Air-Augmented Cluster

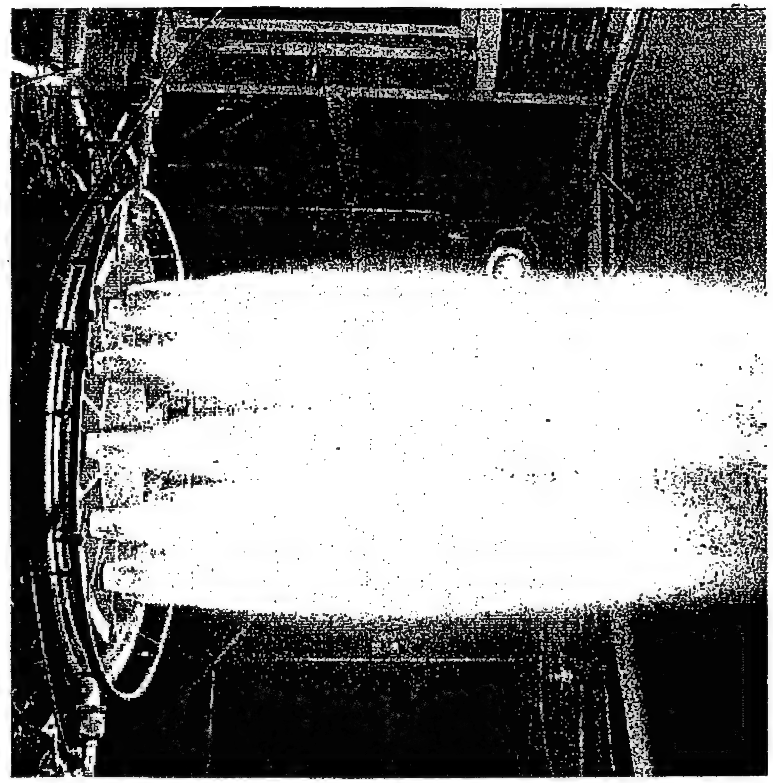


12 Thrust Chamber Cluster at NASA MSFC Test Laboratory

Rocket Engine Nozzle Ejector (RENE)

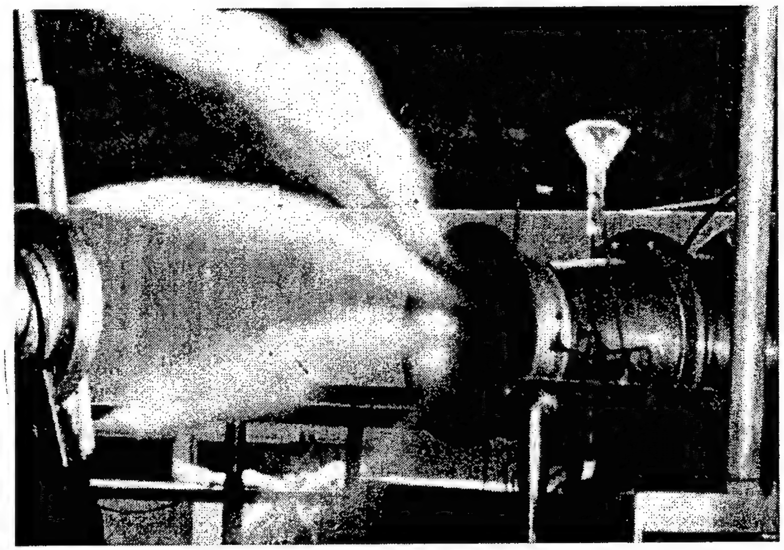


12 Thrust Chamber Cluster at
NASA MSFC Test Laboratory



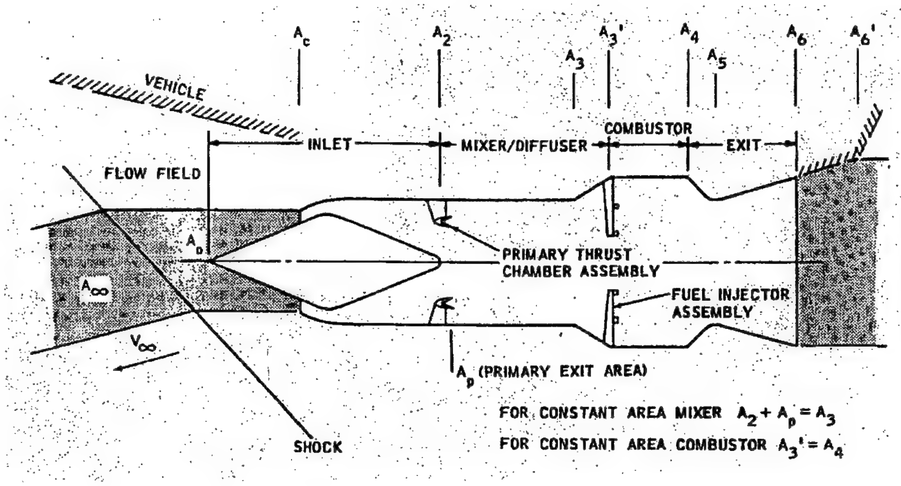
MSFC Rocket Cluster Firing
LO_2 / RP-1, 12x500 lb_f-thrust, 1000 psi

Inlet Flow Entrainment



- Ejector (primary) rocket provides inlet airflow entrainment (Mach 0-3)
  - Operates on the principle of mixing between two streams of gas
  - Mixer length constitutes a performance loss in terms of drag, weight,etc,
  - Various mixing enhancement techniques have been explored.
  - Additional research in this area is needed to better understand and optimize the cycle.
- Inlet (secondary) airflow provides substantial rocket performance augmentation
  - Induced air mixes and burns with fuel-rich gases from the primary rocket exhaust
  - Improvements occur in both engine thrust and Isp

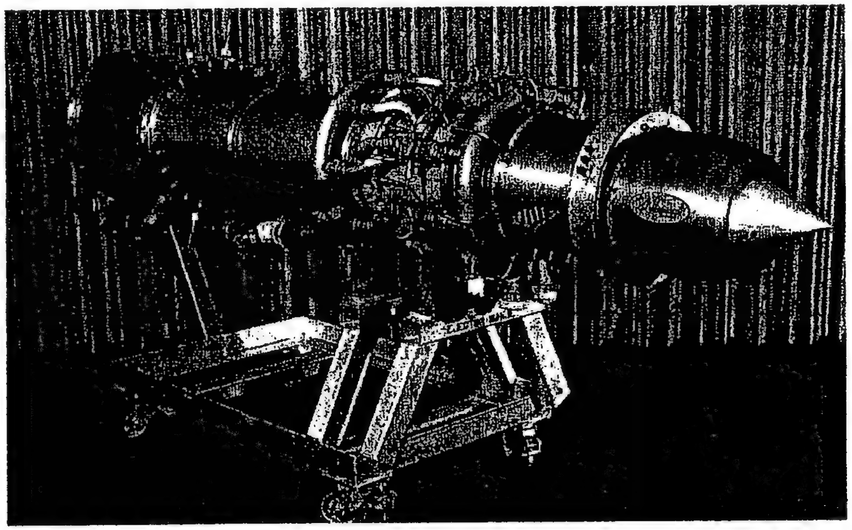
The Ejector Ramjet Engine



Ejector Ramjet Engine Schematic
(with Flowpath Stations Noted)

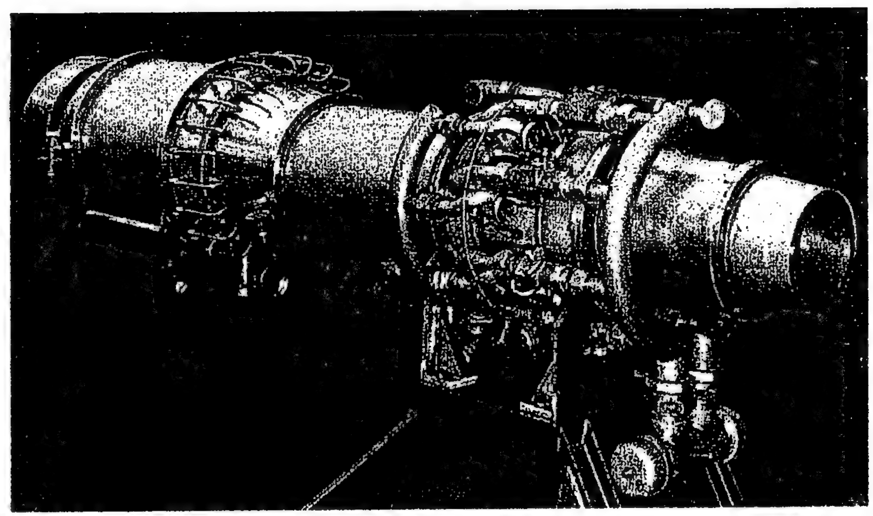
- **Extensive RBCC ejector ramjet testing conducted from 1964-68**
  - Air Force Aero Propulsion Laboratory (Sponsor)
  - The Marquardt Corporation
  - Explored both ejector and ramjet modes (Mach 0-6 range)
- **Subscale "boilerplate" engines built and tested (16-18" dia.)**
  - Regeneratively cooled
  - Fixed and variable area throats (translating plug nozzle)
  - Hydrogen / oxygen propellants
  - Hydrogen-peroxide / JP-4 propellants

The Ejector Ramjet Engine

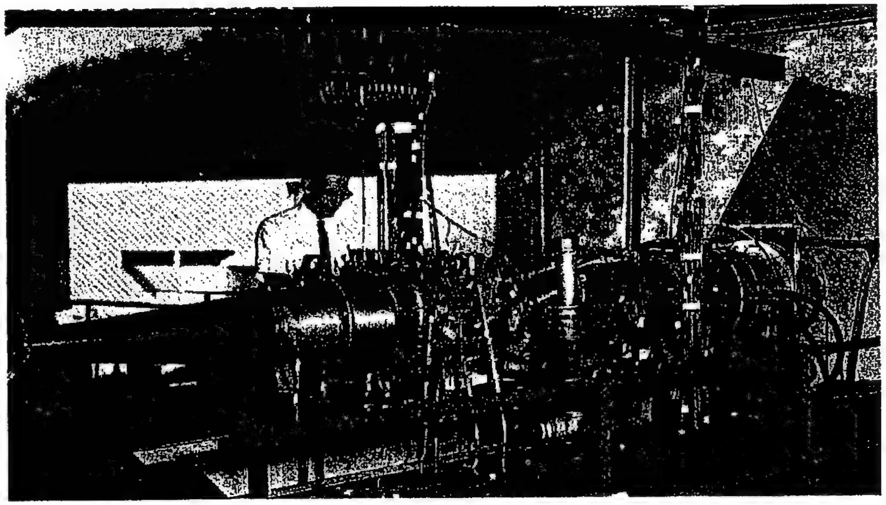


USAF / Marquardt Ejector Ramjet
Subscale Ground-Test Engine (1965)
Hydrogen / Oxygen Propellants
as Initially Configured

USAF / Marquardt Ejector Ramjet
Subscale Ground-Test Engine (1966)
Hydrogen / Oxygen Propellants



The Ejector Ramjet Engine



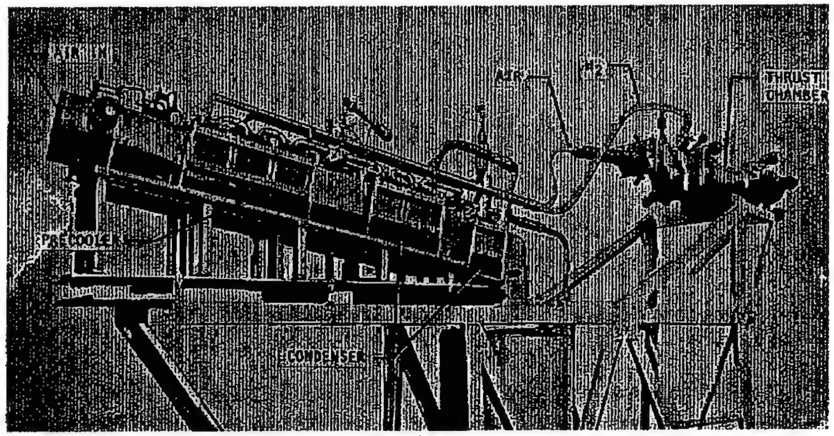
USAF / Marquardt Ejector Ramjet
Subscale Ground-Test Engine (1967)
Hydrogen Peroxide / JP-4 Propellants

Ejector Ramjet Engine Under Test
in Ejector Mode (H_2O_2 / JP-4)

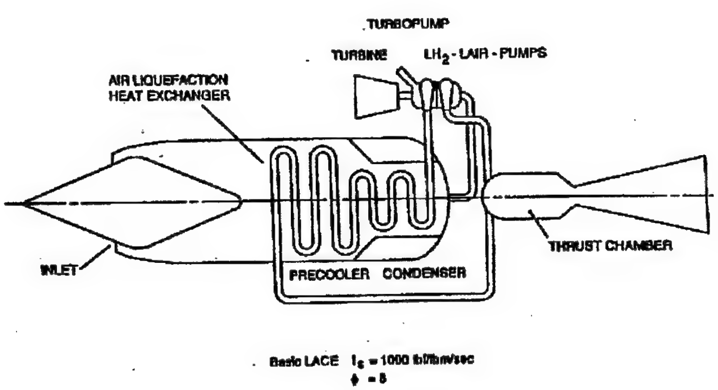
Integrating RBCC and LACE

- **RBCC was only one of several innovative engine types**
  - Interest existed in exploring potential uses of cryogenic hydrogen
  - Various applications were examined in the late 50s, early 60s
- **Experimental work included the Liquid Air Cycle Engine (LACE)**
  - Practical application of cryogenic hydrogen fuel
  - LAIR served as the rocket oxidizer combusting with hydrogen
  - SLS Engine Isp could Triple that of the ERJ (1300-1400 sec)
- **Primary rockets in the RBCC could operate at an O/F = 34:1**
  - Offered unprecedented performance for the propulsion community
  - Came with the cost of additional (and often complex) hardware
  - Came with the cost of certain operational complications
- **The basic LACE was literally an airbreathing rocket engine**
  - Several high performance engine concepts were derived

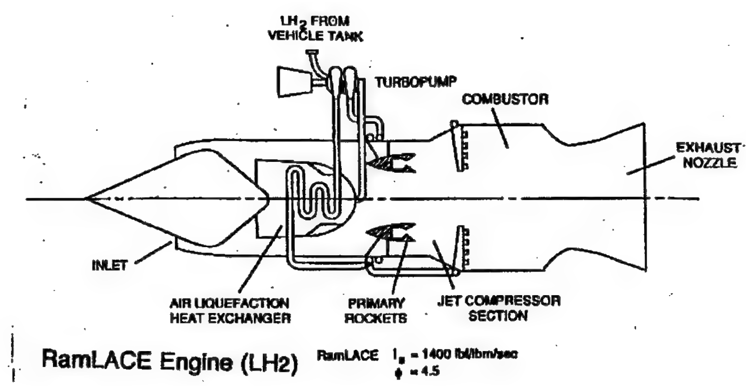
Liquid Air Cycle Engine



Basic LACE Engineering Test Apparatus

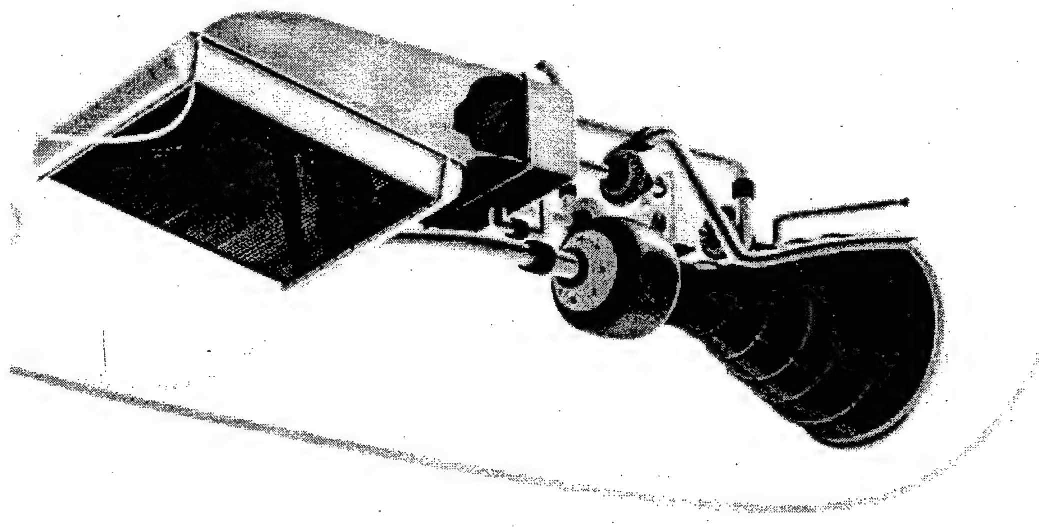


Basic Liquid Air Cycle Engine (LACE)



RBCC LACE Ejector Ramjet (RAMLACE)

Flightweght LACE Concept



- LACE was originated by Marquardt in 1957
  - Charles Lindley and the late Carl Builder were the inventors
  - Requires a series of compact cryohydrogen heat exchangers
  - Operation is constrained by thermal balances and temperature difference
  - Needs far more hydrogen than required for stoichiometric combustion
- LACE remains an attractive option up to speeds in the range of Mach 5-6
  - Performance falls off drastically at higher speeds due to inlet momentum penalties
  - A diverse set of approaches were explored to further enhance performance

The NAS7-377 Study

"A Study of Composite Propulsion Systems for Advanced Launch Vehicle Applications"

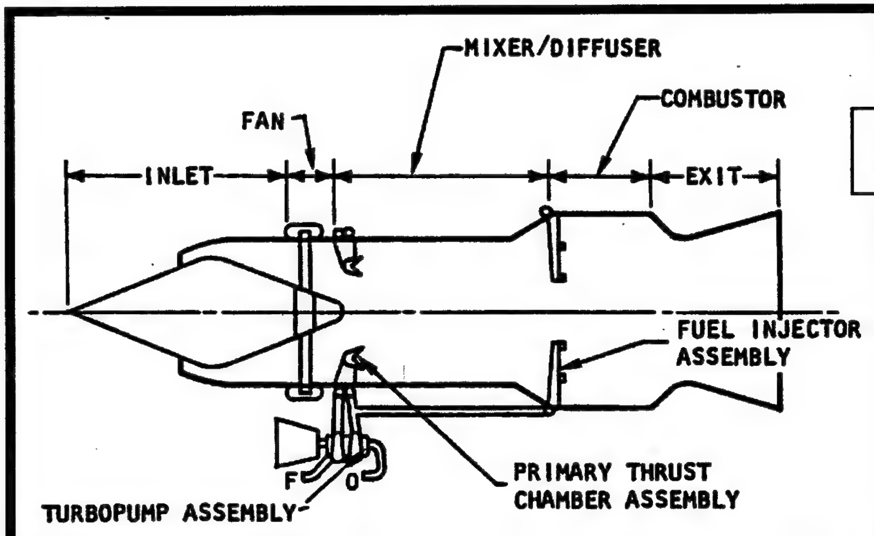
- A systematic assessment of the significance and merits of a variety of composite propulsion systems in the post-1975 period
  - Provided a detailed examination of technology ramifications
  - Emphasized critical or pacing technology requirements
  - Successfully "sorted out" and defined the leading contenders
- NASA contract was awarded in 1966 to a Marquardt-led team
  - Rocketdyne's rocket expertise complemented TMC's A/B forte
  - Lockheed California provided the hypersonic vehicle design expertise
- Emphasis was on two-stage horizontal takeoff and landing concepts
  - First stage was powered by a range of "composite" A/B - rocket engines
  - Second stage used advanced hydrogen / oxygen rocket propulsion

The NAS7-377 Study

Composite Engine Powered Lockheed TSTO Vehicle at Staging (NAS7-377 Study)

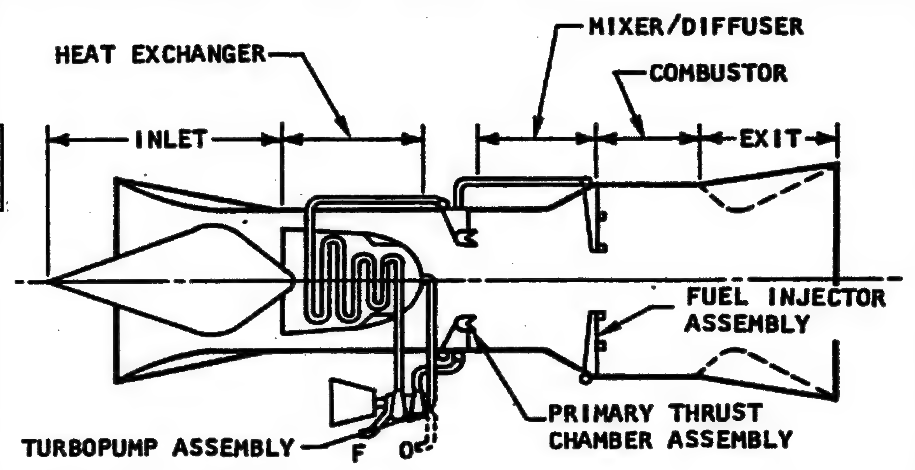
- Study provided for a progressive screening down of engine concepts
  - From original 36 to 12, and finally to 2
  - The analysis and design level of each selection was progressively increased
- The "finalist" engines turned out to be:
  - Supercharged Ejector Ramjet (SERJ) engine (nearer-term technology)
  - ScramLACE (SL) engine ("further out" technology)

NAS7-377 Selected Engines



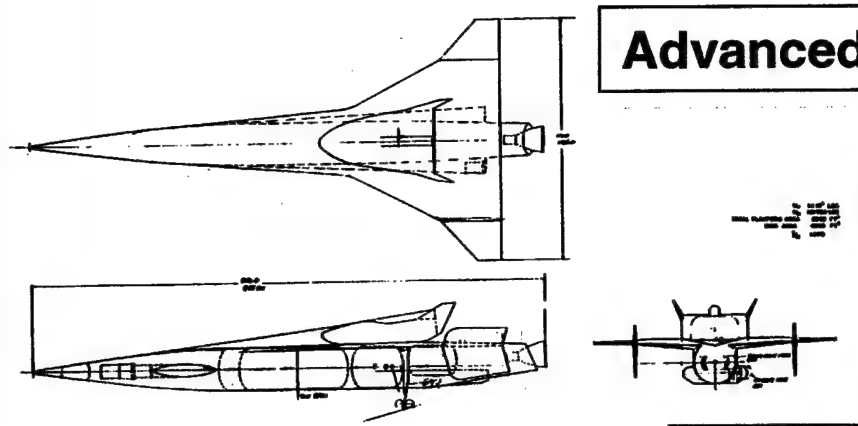
Supercharged Ejector RamJet

ScramLACE

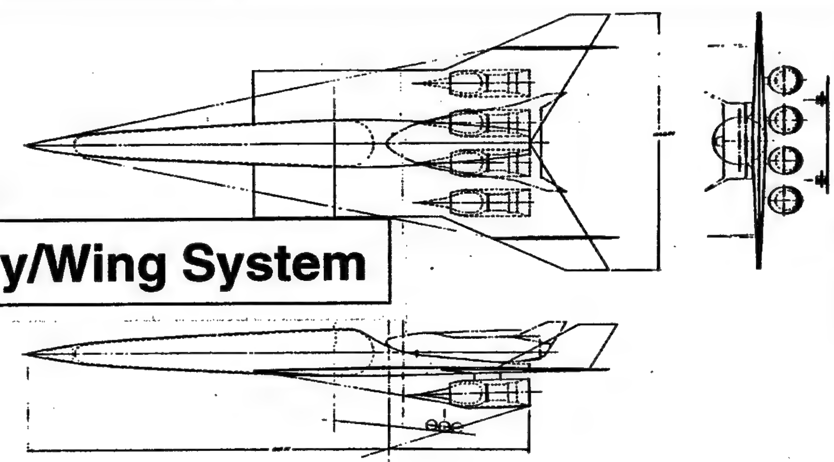


NAS7-377 Vehicle Concepts

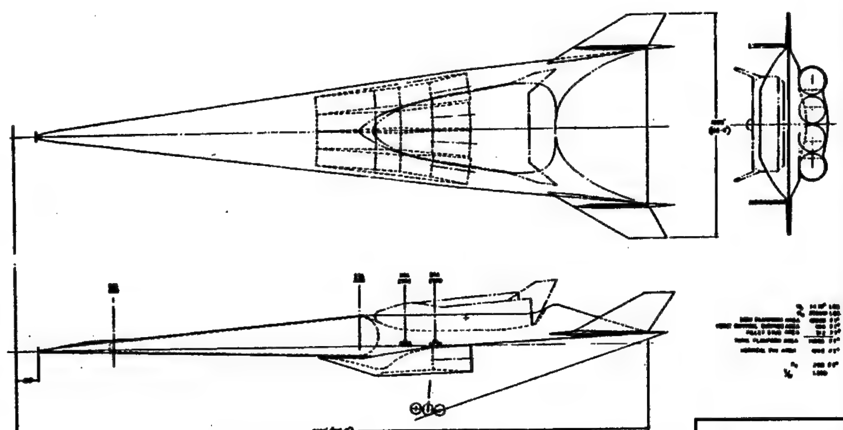
Advanced Rocket System



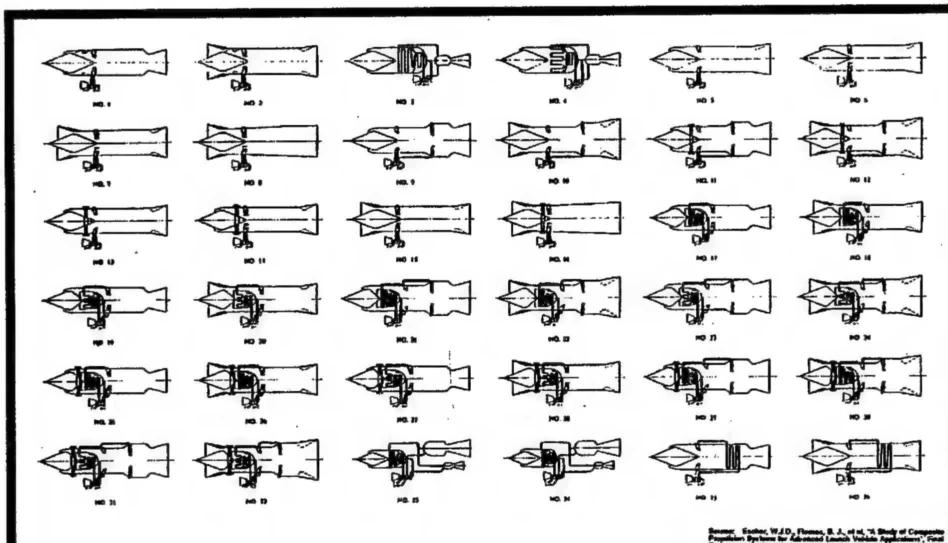
Cylindrical Body/Wing System



Lifting Body System

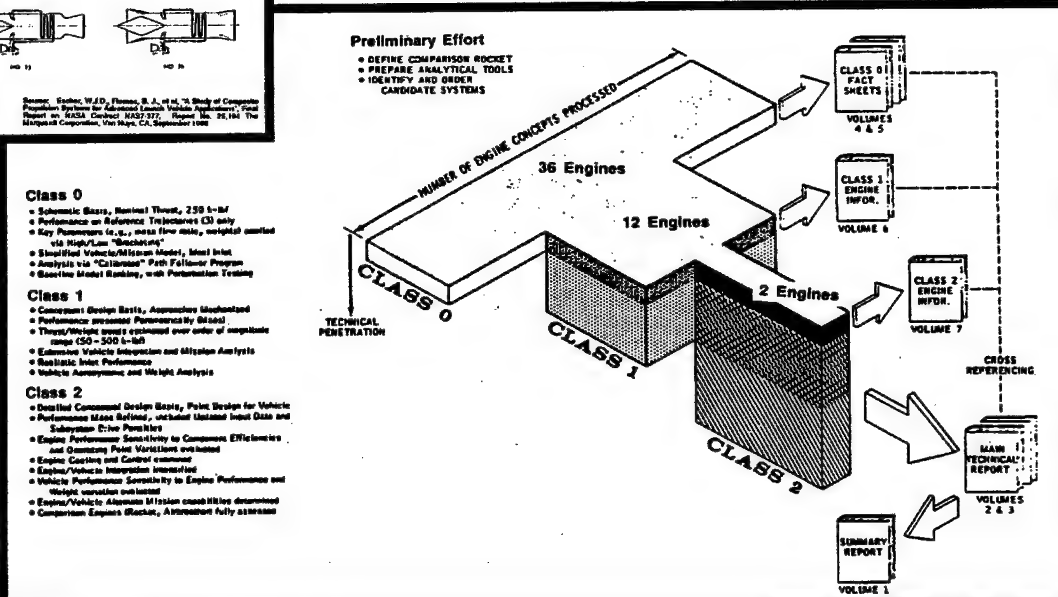


NAS7-377 Lessons Learned



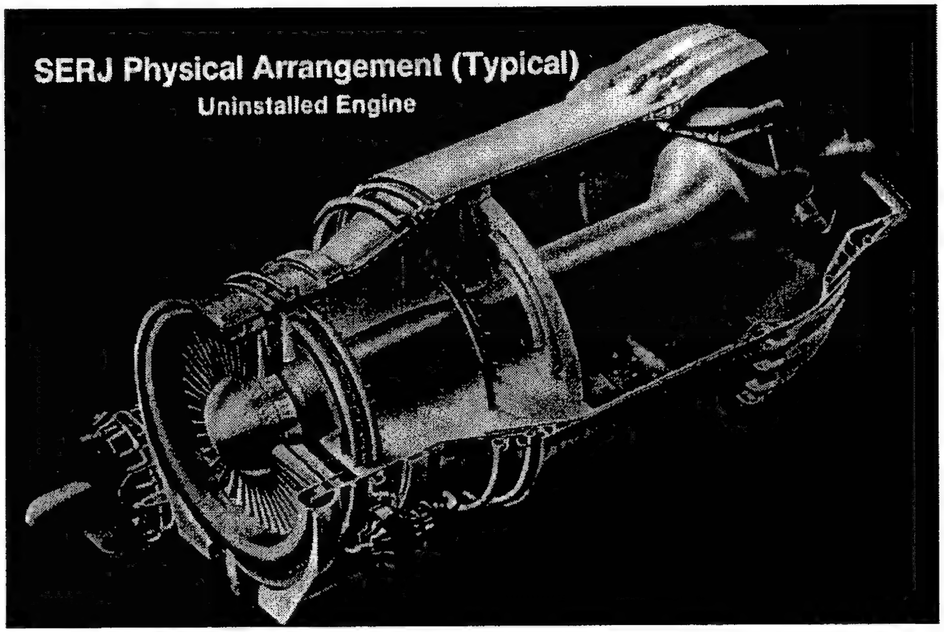
Source: Escher, W.J.D., Flornes, B.J., et al, "A Study of Composite Propulsion Systems for Advanced Launch Vehicle Applications", Final Report on NASA Contract NAS7-377, Report No. 25,194 The Marquardt Corporation, Van Nuys, CA, September 1966

The Study Results Still Serve the RBCC Community Today.



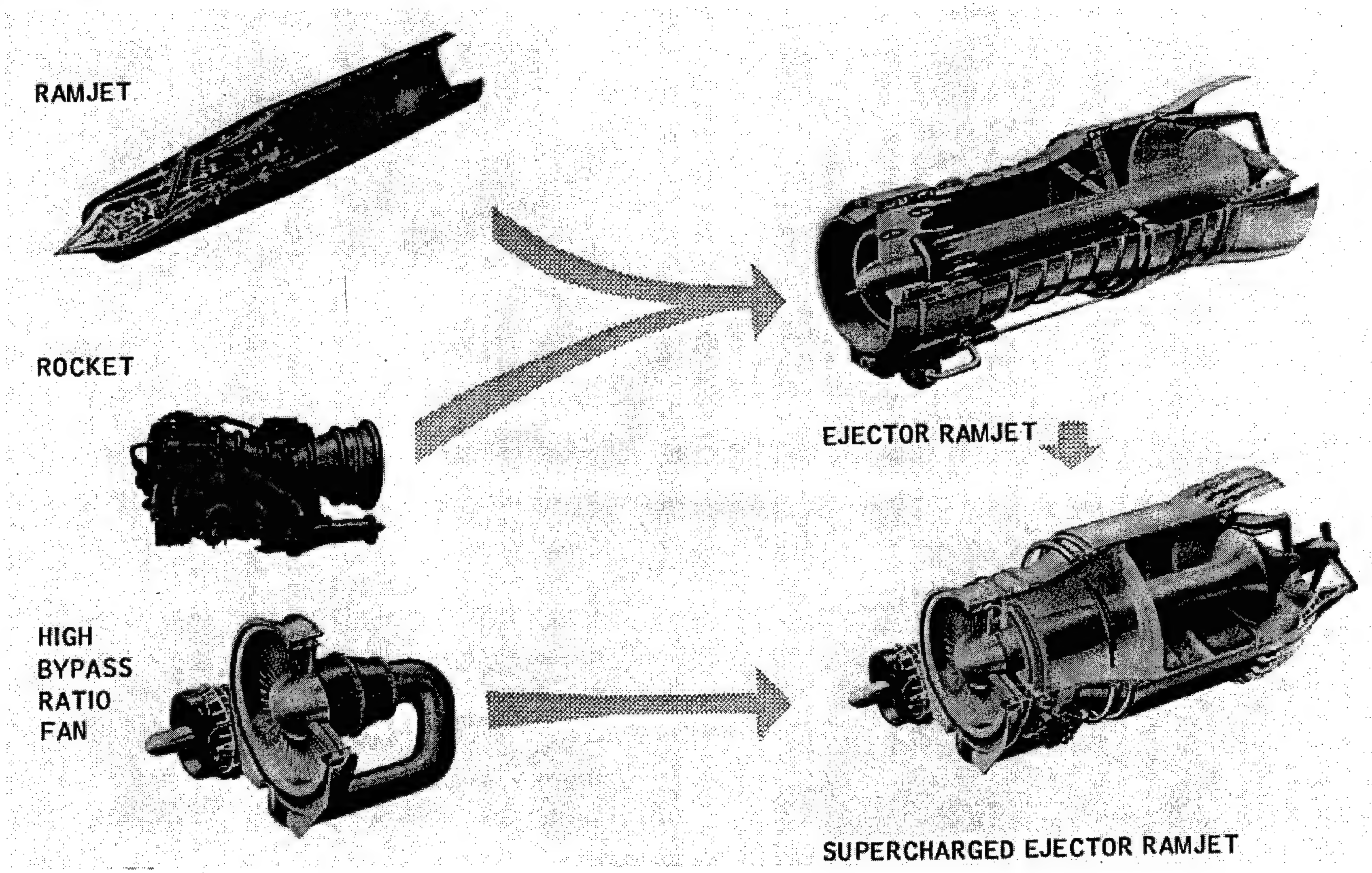
Same Methods and Techniques Should be Used to Conduct Integrated Performance Analysis.

NAS7-377 Study



- SERJ and SL surpassed the all-rocket and composite cycle comparison cases.
  - Composite cycle propulsion is a strong competitor for advanced launch vehicles.
- NASA elected to support an "extension phase" effort.
  - Marquardt / Rocketdyne / Lockheed team provided further design details.
  - Conducted special studies on points of interest emerging from the basic study
  - All total, a nine volume final report set resulted

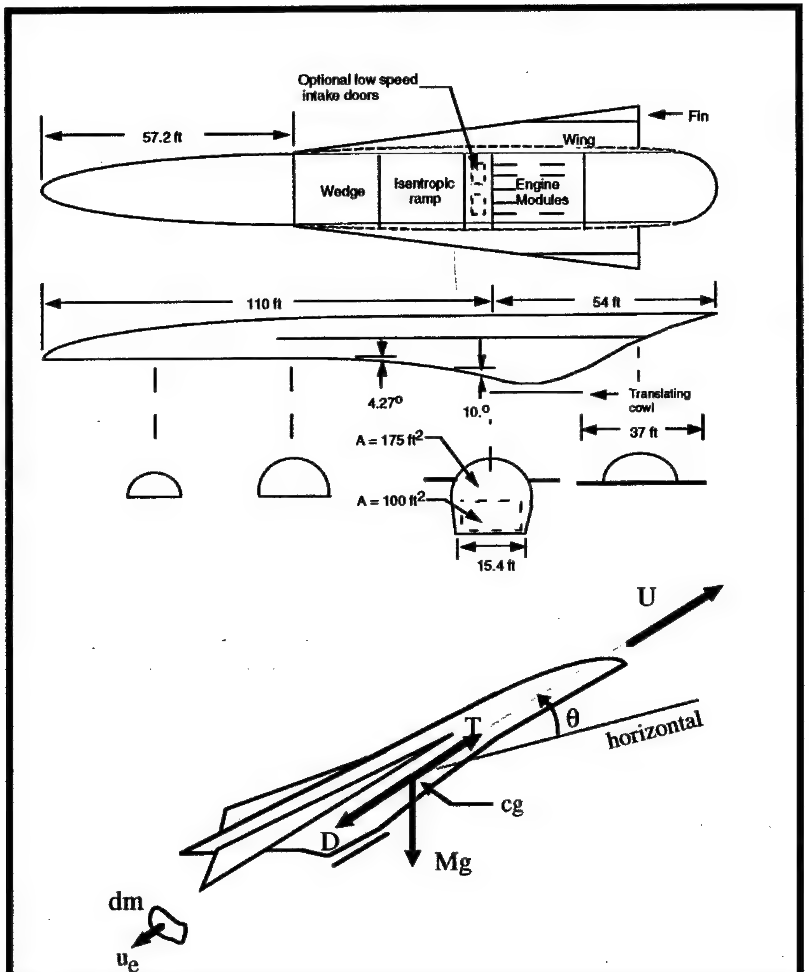
Genesis of SERJ



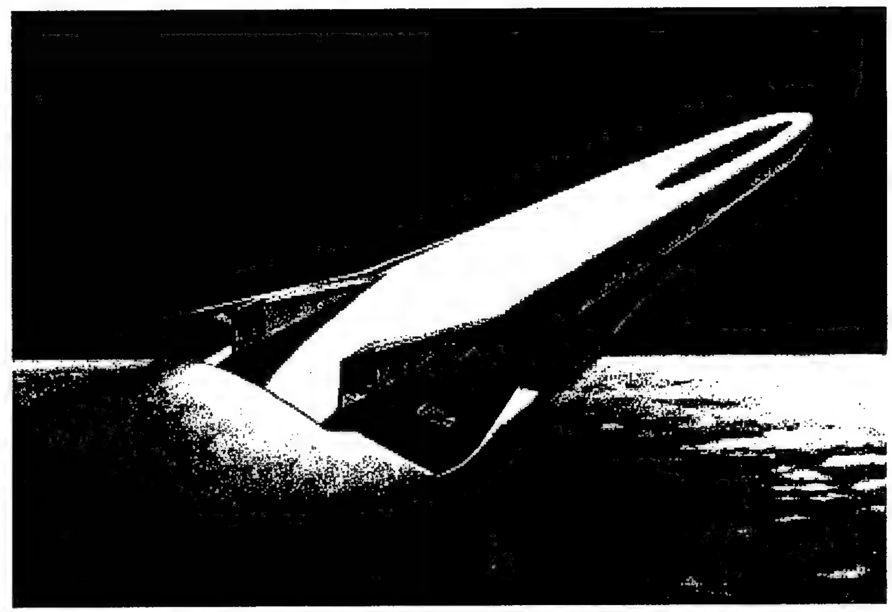
Integrated Performance Analysis

- We can build from what was learned in the past.
  - Methodologies are about the same
  - Tools have changed since the mid-1960s.
  - Make use of available databases.
- There is a better understanding of the requirements for reusable space transportation
  - Focus on performance analysis
  - Incorporate broad analytical trade studies
- Design support must be provided by:
  - Propulsion
  - Structures
  - Aerodynamics
  - Aerothermodynamics
  - Mass properties
  - System level optimization

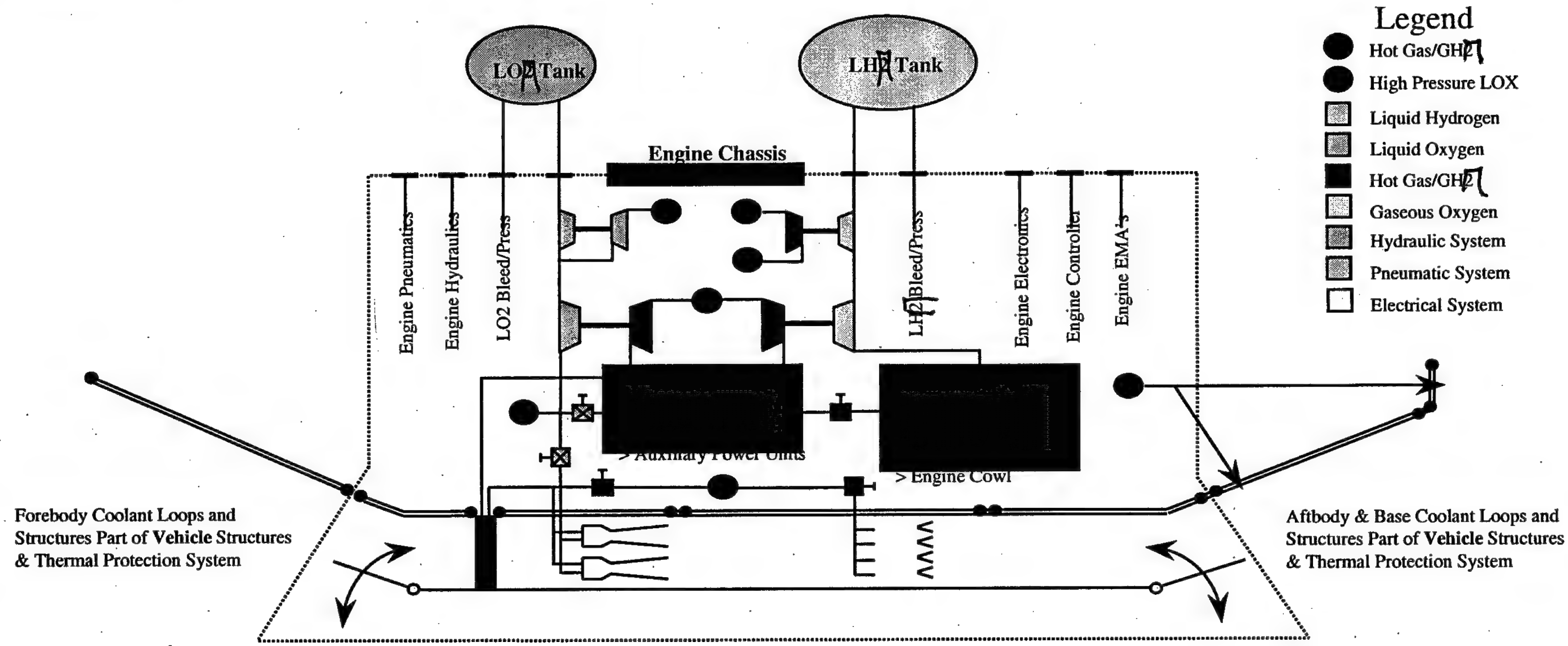
Integrated Performance Analysis



RBCC Propelled SSTO Concept



RBCC Engine Envelope



Inlets & Isolators
> Structures
> Coolant Loops or TPS
> Diverters & Bleed Mechanisms
> Variable Geometry Surfaces & Seals

Ejector System
> Thrusters, Manifold Struts
> Injectors, Ignitors
> Coolant Loops

Combustor
> Structures & Coolant Loops
> Injectors & Flame Holders
> Variable Geometry Surfaces & Seals

Nozzle
> Structures
> Coolant Loops or TPS
> Variable Geometry Surfaces & Seals

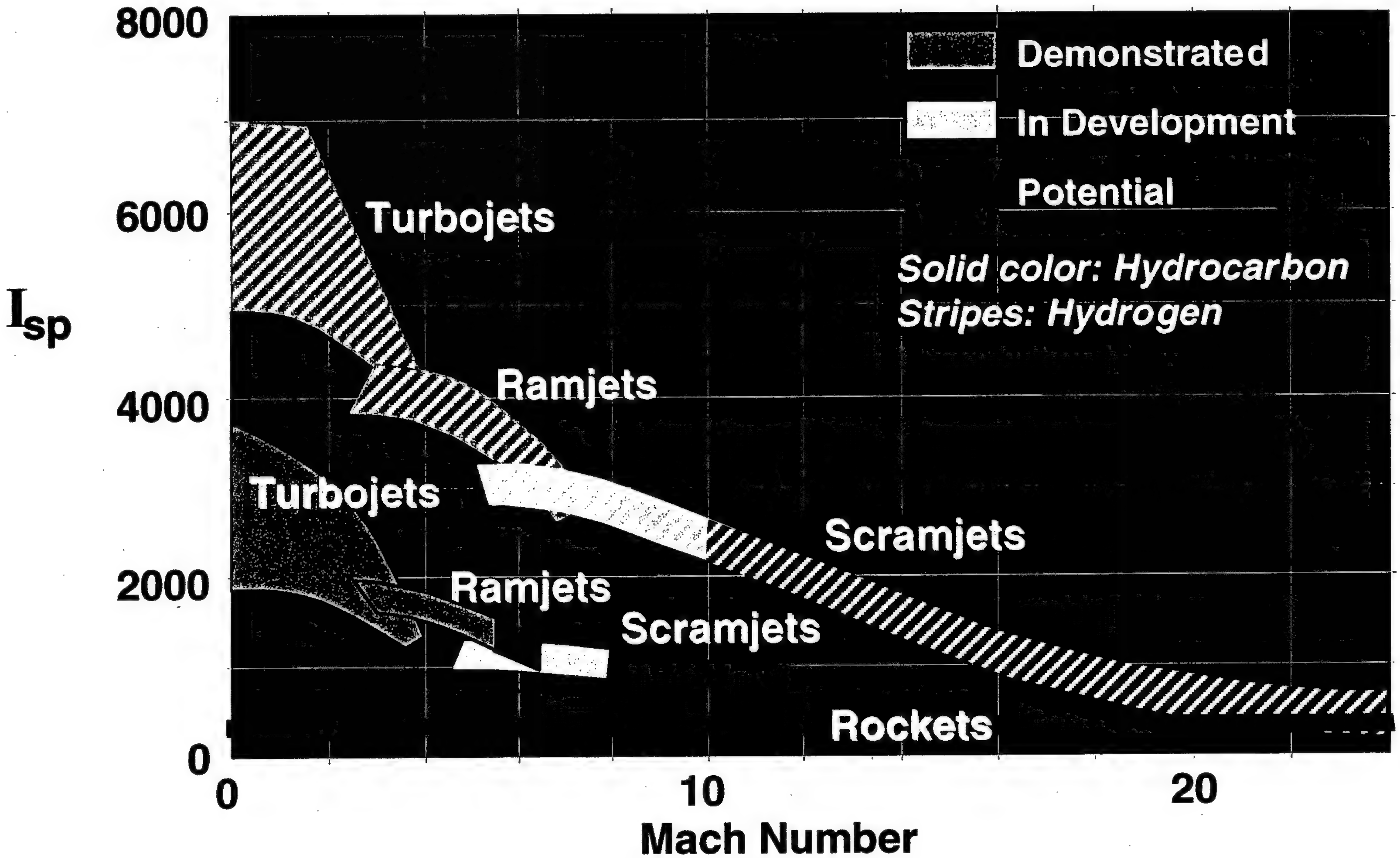
Supercharging Fan
> Fan & Retract Mechanisms
> Bypass Ducts

Engine Chassis
> Thrust Structure Part of Vehicle
> Chassis Part of Engine and Mates to Thrust Structure

External (Aftbody & Base) Burning
> Feedlines, Injector
> Not Including Surfaces (Vehicle)

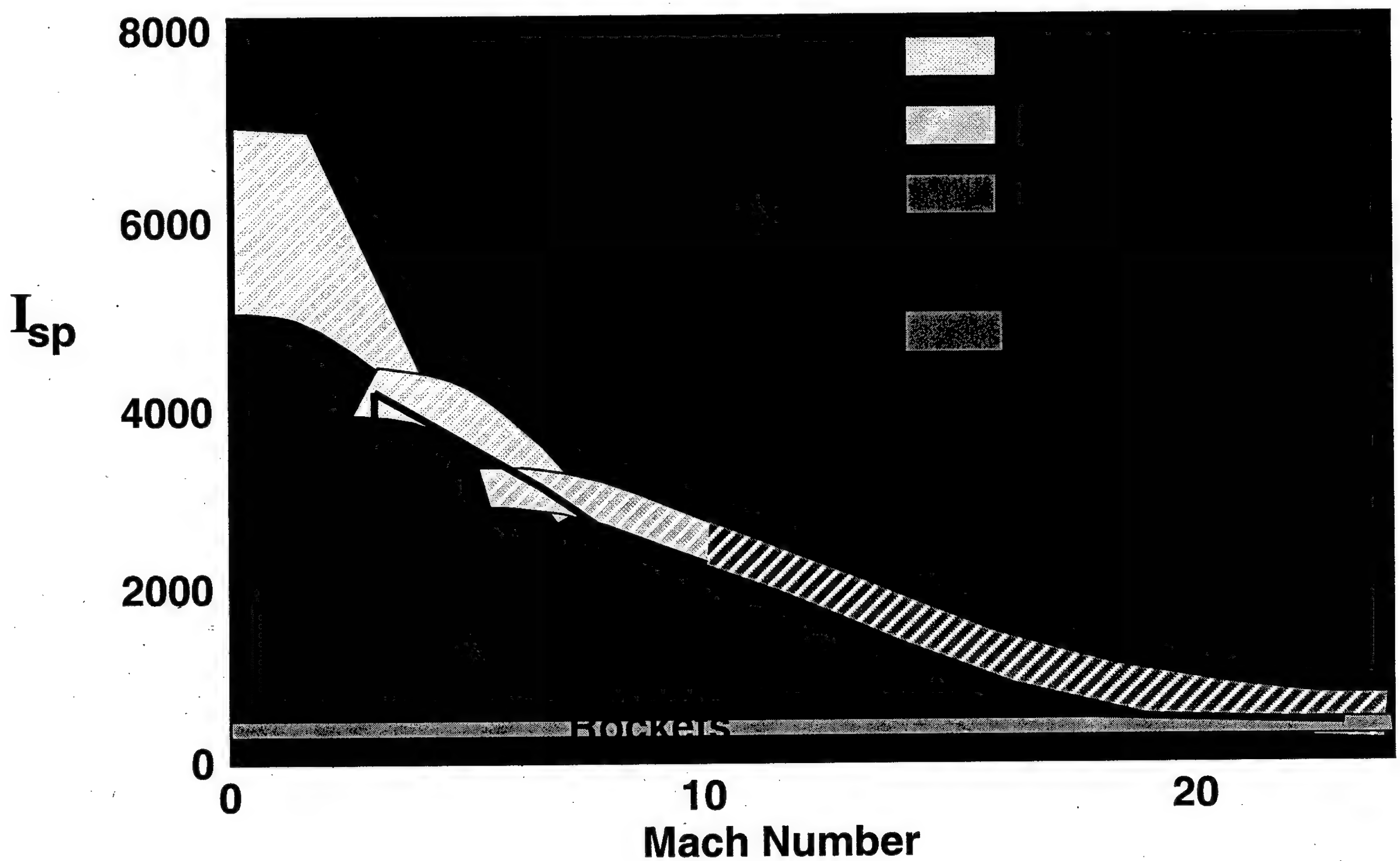
D.R. Komar/EP13

Airbreathing Engine Performance Profiles



Note: Hydrocarbon fuels offer logistically supportable aircraft-like operations.

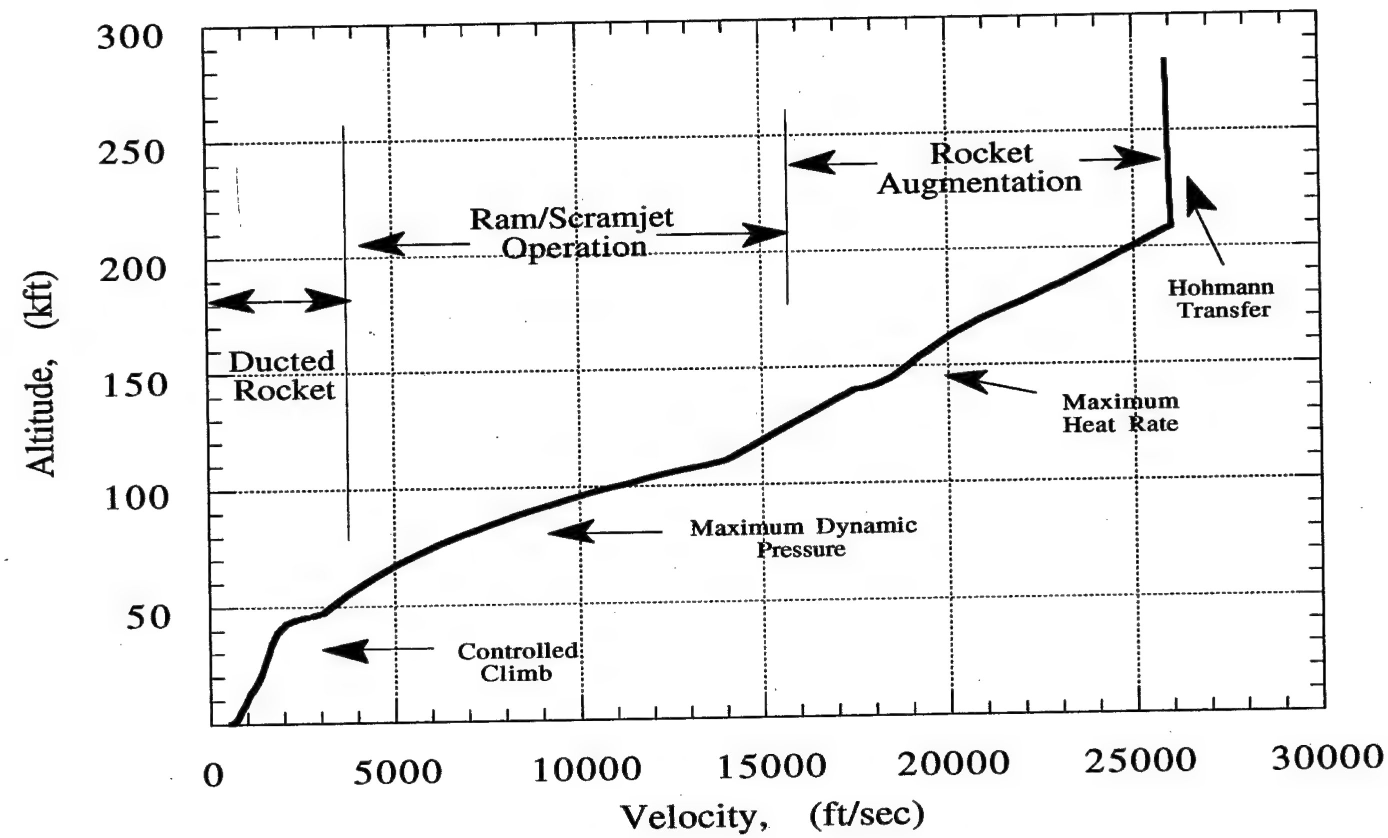
Airbreathing Engine Performance Profiles



Note: Hydrocarbon fuels offer logistically supportable aircraft-like operations.

Representative RBCC Flight Profile

SSTO Trajectory Simulation



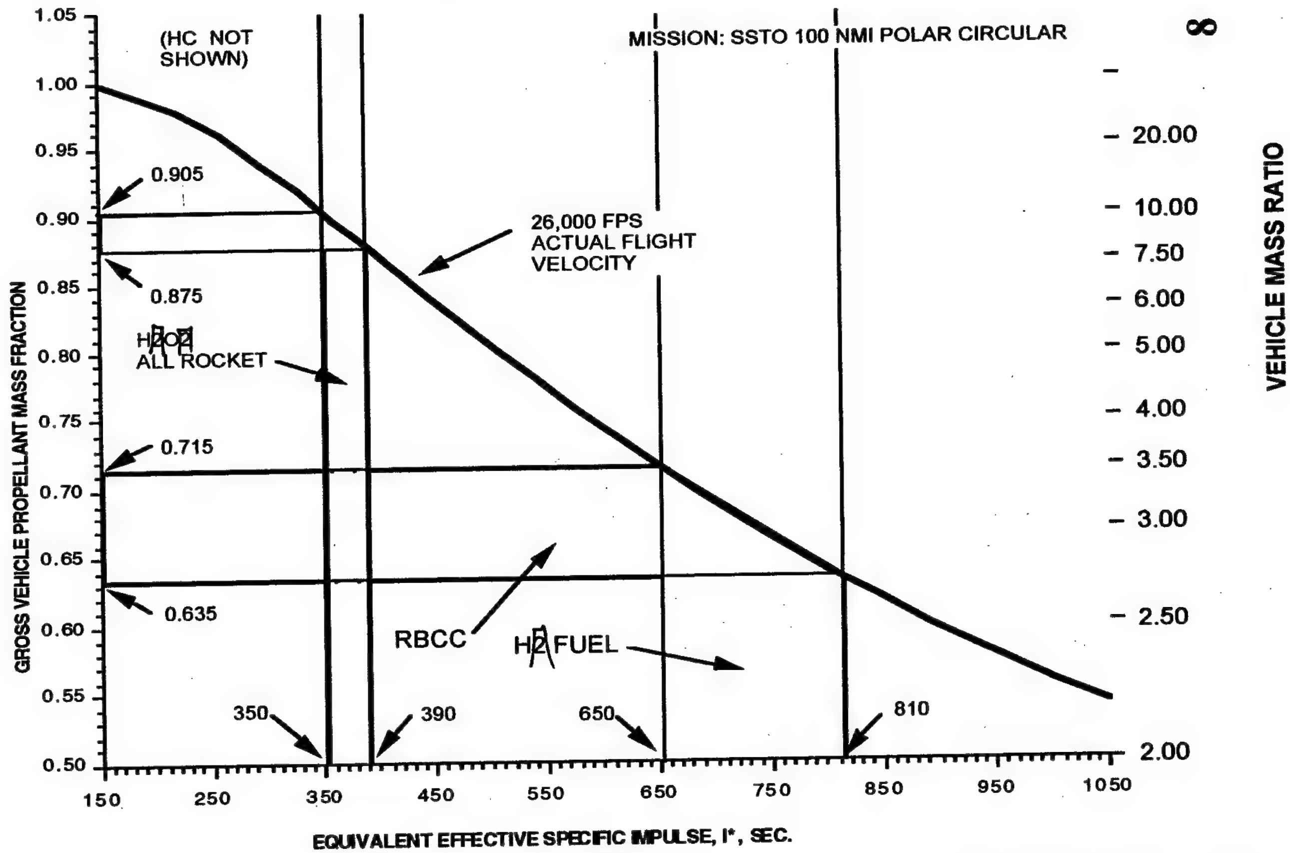
Payoffs of Combined Cycle Engines

- Lower gross takeoff weight for a given payload
- Improved engine specific impulse
  - Rocket Isp 455 sec (vacuum)
  - RBCC Isp 2200 sec (Mach 10)
- Relaxed vehicle mass fraction requirements
  - Rocket SSTO 0.88 - 0.91
    TSTO 0.85 - 0.86
  - RBCC SSTO 0.64 - 0.72
    TSTO 0.57 - 0.64
- Increased flight performance and maneuvering capability
  - All inclination flight
  - Longer duration launch window
  - Increased safety (abort options)

Comparison of I* versus Mass Fraction for All-Rocket and RBCC Systems

GRAPHICAL PORTRAYAL OF THE MODIFIED IDEAL ROCKET EQUATION SHOWING CHARACTERISTIC PERFORMANCE AND PMF RANGES FOR ALL-ROCKET AND RBCC PROPULSION

7



NASA RBCC Paper

Two-Stage vs. Single-Stage-To Orbit

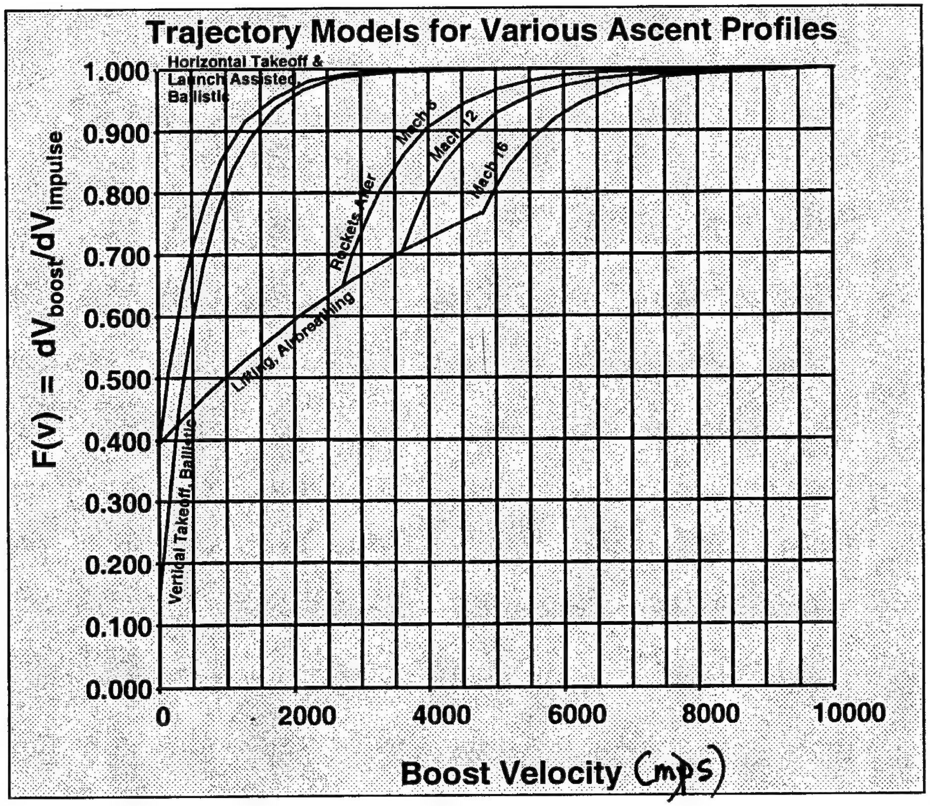
- We're still trading two-stage versus single-stage-to-orbit.
- Conventional wisdom says SSTO least costly.
  - Maintaining one vehicle cheaper than two
  - Vehicle mating operations eliminated
  - Flight operations simplified
  - BUT,
    - Required mass fractions are elusive.
    - Payload bay volume dominated by propellant volume.
    - Weight margins easily exceed payload weight.
- Two stage systems are more forgiving in design.
  - Less dependence on advanced technologies required.
  - Lift-off mass doesn't go all the way to orbit and back.
  - Less sensitive to weight growth
  - Denser hydrocarbon propellants are attractive.

AFRL Parametric Comparison of Hypersonic Space Lift and Global Reach Concepts

<u>Each Concept has been Parameterized</u>.

– **Propulsion Characteristics**
– **Vehicle Mass Fractions**
– **Trajectory**

Ascent Trajectory Modeling



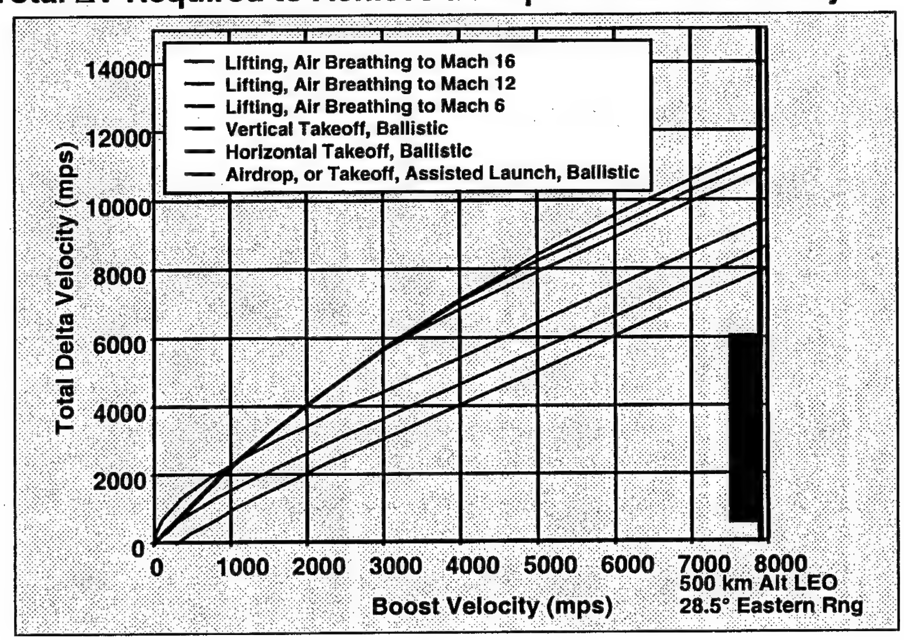
$$\Delta V = \int_{V_o}^{V_f} \frac{1}{F(V)} dV$$

where: F(V) is the ratio of the actual change in velocity to ΔV invested

V_o is the initial velocity

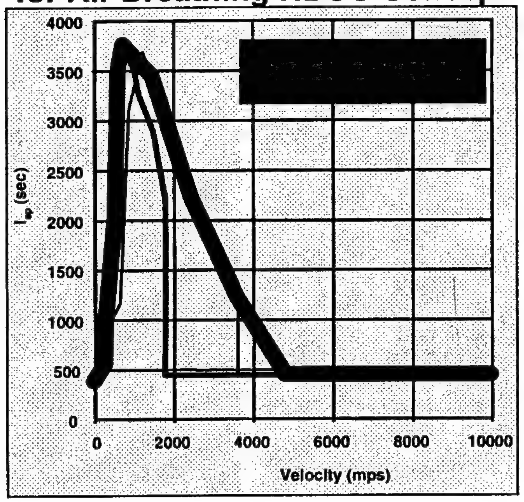
V_f is the final boost velocity

Total ΔV Required to Achieve a Required Boost Velocity



Effective Isp and Ascent Profile Modeling

I_{sp} vs Velocity
for Air Breathing RBCC Concepts



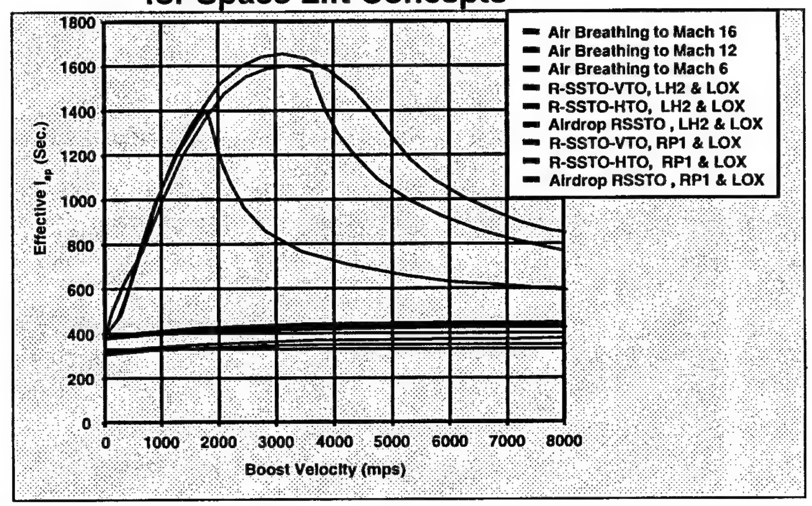
$$I^e_{sp} = \frac{\int_{V_o}^{V_f} \frac{1}{F(V)}\, dV}{\int_{V_o}^{V_f} \frac{dV}{F(V) I_{sp}(V)}}$$

where: $F(V)$ is the ratio of the actual change in velocity to ΔV invested

V_o is the initial velocity

V_f is the final boost velocity

Effective I_{sp} vs Boost Velocity
for Space Lift Concepts



- **Airbreathing propulsion assumptions:**
  - All concepts assuming LH2 fueled Rocket Based Combined Cycle engines of various designs
  - Air Breathing to Mach 16: Assumes an approximate model from NASP
  - Air Breathing to Mach 12: Assumes a model from the Aerojet Strutjet project
  - Air Breathing to Mach 6: Assumes a model from NASP history
  - All concepts assume LH_2 & LOX rocket propulsion at higher Mach numbers
- **Single, or first, stage rocket propulsion assumptions:**
  - Two broad categories assumed:
    - Hydrocarbon & LOX, $I_{sp} \approx 340$ sec vac
    - LH_2 & LOX, $I_{sp} \approx 450$ sec vac
- **Upper stage propulsion, when applicable, $I_{sp} \approx 320$ sec vac**

Vehicle Mass Accounting
Space Lift Concepts

Payload delivered to orbit the key performance "Figure Of Merit" (FOM) for space lift concepts

- **Greater than zero means it is feasible**
- **Relative merit when compared to other concepts**
- **A key parameter which determines cost**

Performance FOM:
Payload Weight to Gross Takeoff Weight Ratio

$$\frac{M_c}{M_o} = \frac{MR + MF - 1}{MF}$$

-or-

$$\frac{M_c}{M_o} = 1 - \frac{(1 - MR)}{MP} - \frac{f}{TW_e}$$

Mass Accounting of the Vehicle Concepts

$$M_o = M_s + M_p + M_e + M_c$$

where:
- M_o is the mass of the vehicle at takeoff
- M_s is the dry mass of the vehicle without the engine
- M_p is the mass of the propellant
- M_e is the mass of the engines
- M_c is the mass of the payload

- **Simple mass accounting which captures the key mass contributors**
  - **Airframe, Engines, Payload & Propellant**
- **The mass of all concepts are easily parameterized with this accounting**

Other Useful Definitions & Relations

$$MR = \frac{M_o - M_p}{M_o} = e^{-\frac{\Delta V}{I_{sp} g_o}}$$

$$MF = \frac{M_p}{M_p + M_s + M_e}$$

$$MP = \frac{M_p}{M_p + M_s}$$

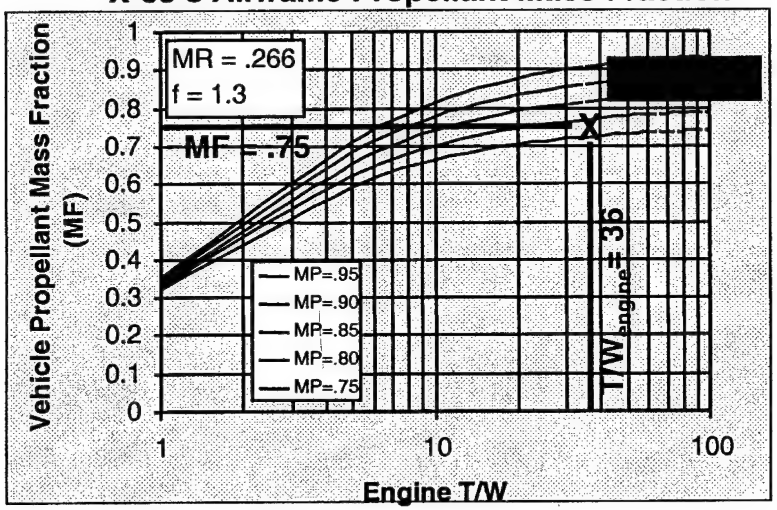
$$MF = \frac{MP(1 - MR)}{(1 - MR) + MP \, f/TW_e}$$

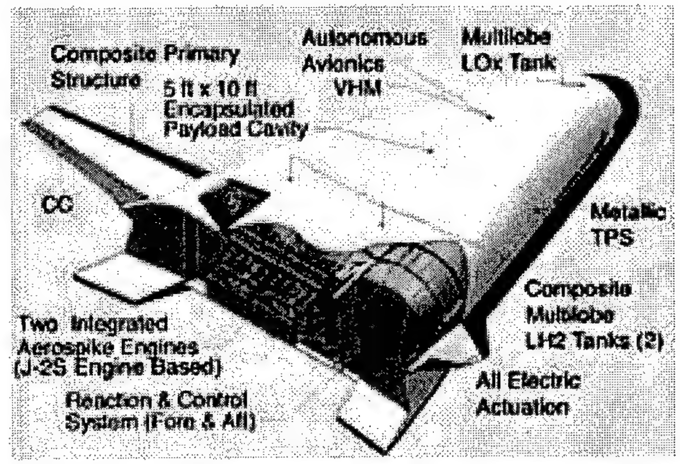
$$MP = \frac{MF(1 - MR)}{(1 - MR) - MF \, f/TW_e}$$

where:
- MR is the vehicle mass fraction
- MF is the propellant mass fraction
- MP is the airframe propellant mass fraction
- f is the vehicle thrust to weight fraction at takeoff
- TW_e is the engine thrust to weight at takeoff conditions

X-33 Provides a Technology Touch Stone

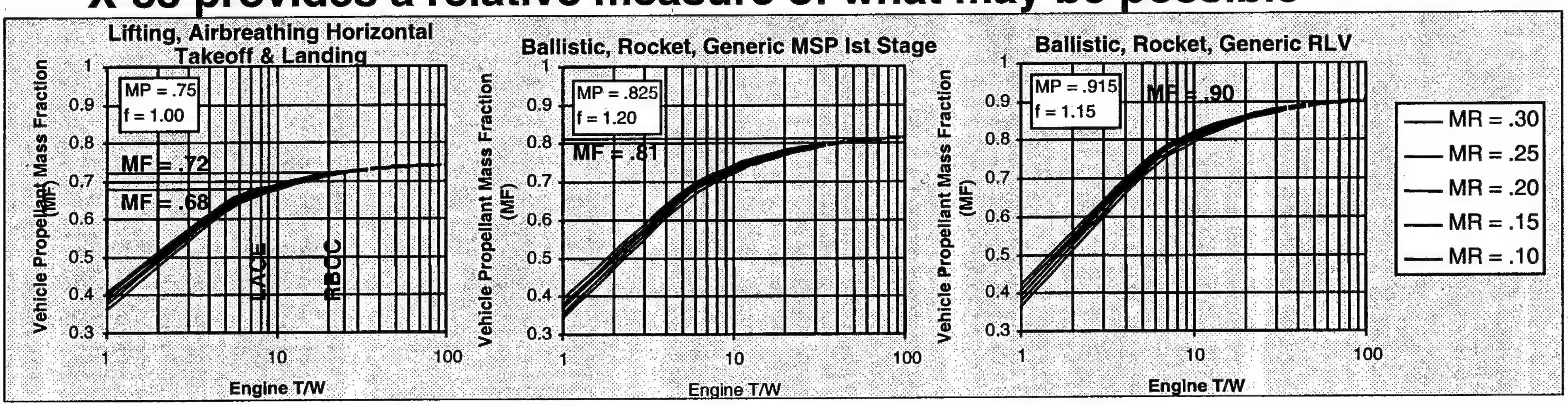
X-33's Airframe Propellant Mass Fraction





X-33's Airframe Demonstrates a Technology Capability

- **For concepts where airframe technology has not been demonstrated, X-33 provides a relative measure of what may be possible.**



Space Lift Concept Comparison

Payload to Orbit Performance Calculations

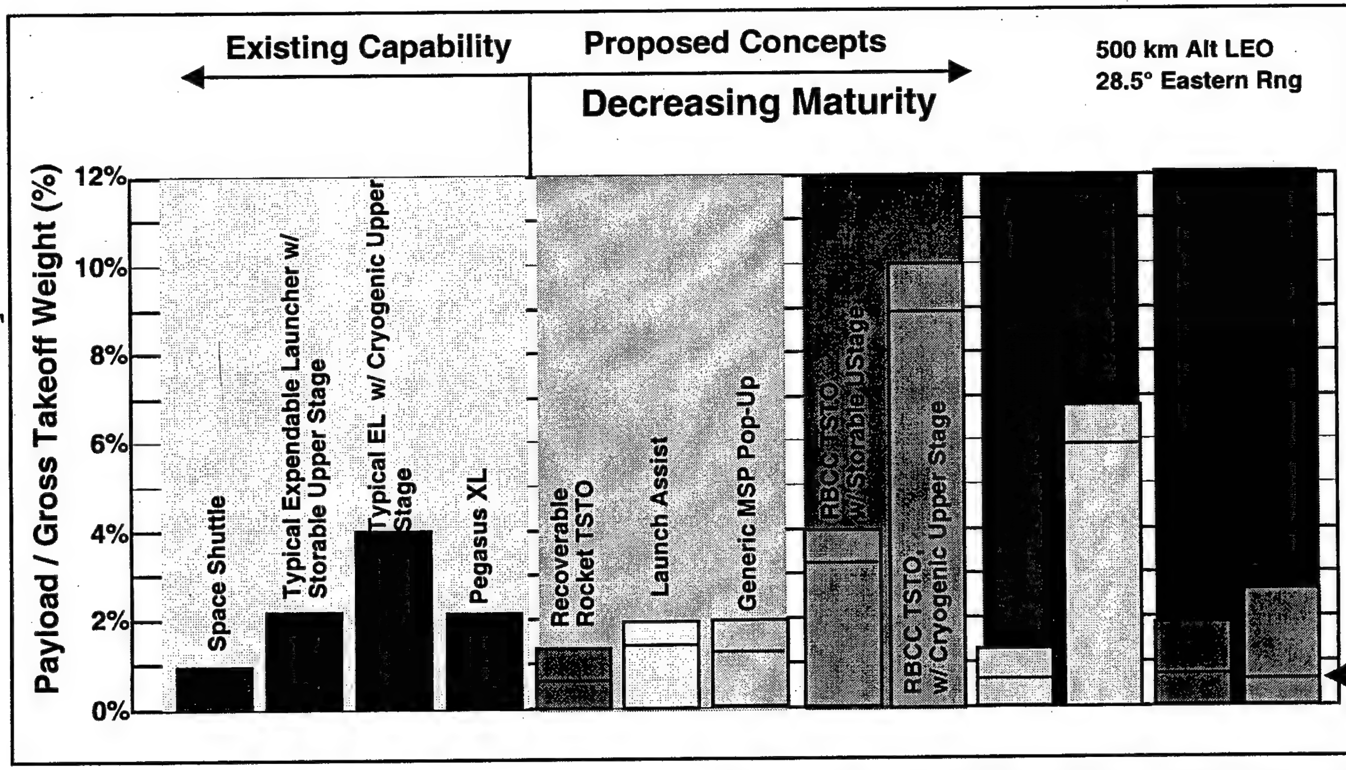
Concept	ΔV_T	ΔV_1	$Eff_1 I_{sp}$	MR_1	T/W_{Eng}	T/W_{Veh}	MP_1	MF_1	M_{d1}/M_0	M_1/M_o	ΔV_2	$Eff_2\ I_{sp}$	MR2	MF_2	M_2/M_1	M_c/M_{dt}	M_c/M_o
RBCC TSTO w/Store. UStg	11160	6340	1586	.666	23	1	.75	.70	.1302	.511	4820	320	.215	.85	.140	18.5%	4.0%
RBCC TSTO w/ Cryo UStg	11160	6340	1586	.696	23	1	.75	.70	.1302	.511	4820	450	.335	.85	.177	55.1%	10.0%
LACE TSTO w/Store UStg	10116	4711	983	.613	12	1	.75	.65	.2084	.401	5405	320	.178	.85	.033	5.2%	1.34%
LACE TSTO w/ Cryp Ustg	10116	4711	983	.613	12	1	.75	.65	.2084	.401	5405	450	.294	.85	.169	26.6%	6.8%
Launch Assist	7250	3624	320	.315	40	1	.78	.76	.2163	.100	3626	320	.315	.85	.194	8.3%	1.9%
Rocket Recoverable TSTO	9200	4600	320	.231	70	1.2	.88	.86	.1252	.109	4600	320	.231	.85	.095	7.4%	1.03%
Generic MSP Pop-Up	9200	5500	426	.268	70	1.2	.83	.81	.1717	.101	3700	320	.307	.85	.185	10.3%	1.9%
Generic Rocket SSTO	9200	9200	435	.116	70	1.15	.915	.90*	.0985	.017	-	-	-	-	-	18.3%	1.7%
							(.83)	(.82)	(.1975)	(-.081)						(-41.3%)	(-8.1%)
Generic RBCC SSTO	11160	11160	730	.210	30*	1	.84	.81*	.1838	.026	-	-	-	-	-	14.2%	2.6%
					(23)		(.75)	(.72)	(.3068)	(-.097)						(-31.6%)	(-9.7%)

* A stated requirement, but not necessarily a demonstrated technology or capability

(##) Estimate from the author's estimate of a achievable technology

AFRL Space Lift Concept Comparison

Excerpt From AFRL/PRST In-House Analysis May 1999



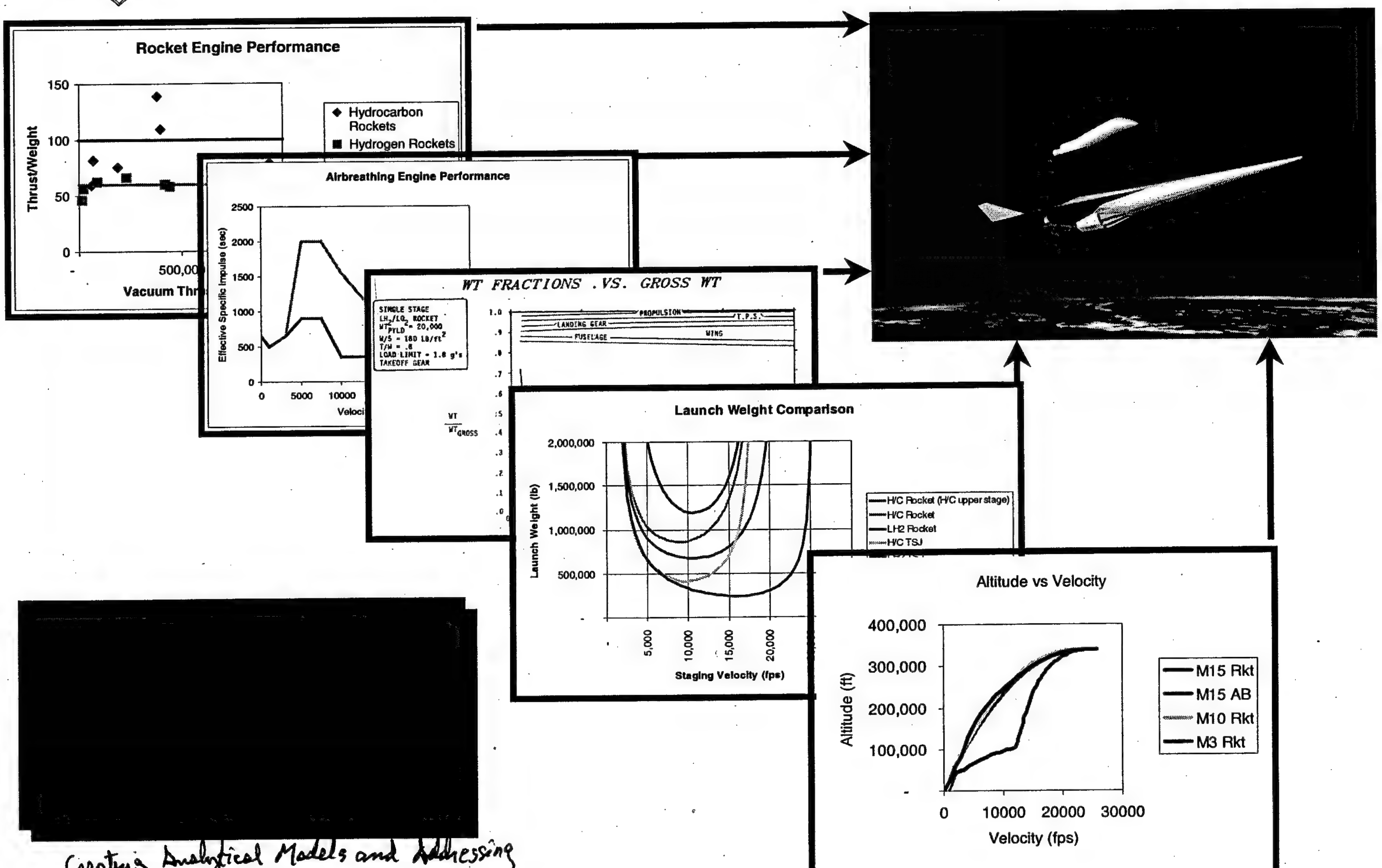
[Water-mark reflects 10% structural mass increase]

- Parametric study of concepts allows "apple-to-apple" comparisons
- Comparison illuminates the potential of each concept
- Emerging propulsion technology offers significant performance improvements

Reusable Military Aerospace Vehicle (RMAV) Study

- Providing an in-depth systems analysis of vehicle concepts designed to accomplish the future requirements for a military spaceplane
  - Focus on TSTO configurations, with various staging Mach numbers
  - Evaluating both all-rocket and combined cycle propulsion options
- Forming multi-disciplinary teams
  - AFRL's Propulsion (PR), Air Vehicle (VA), Space Vehicle (VS) Directorates
  - Aeronautical Systems Center (ASC)
  - Space and Missile Center (SMC)
  - NASA Research Centers (Langley, Glenn, and MSFC)
- Anchoring vehicle performance levels using nationally accepted codes
  - ENG-92 – APAS – CONSIZ - ROCETS
  - POST – RJPA – RAMSCRAM - Etc.
- Conducting a detailed, iterative synthesis process involving many design parameters and internal variables
  - Including assessment of technology readiness and development schedule

Integrated Performance Analysis



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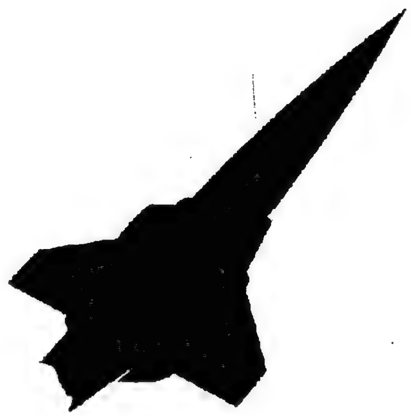
Creating Analytical Models and Addressing
Vehicle Integration Issues For

NASA Glenn Research Center

NASA Lewis Research Center

Trailblazer Vehicle



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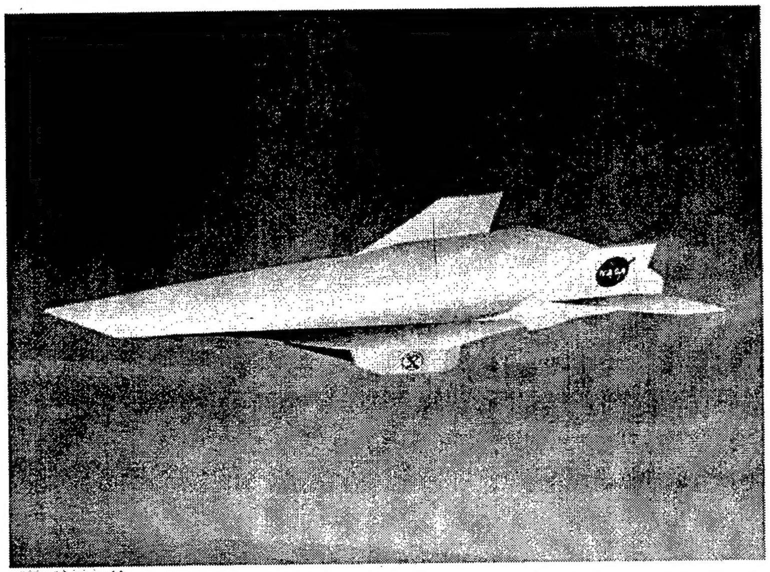
An Aggressive RBCC Propulsion System Development

Trailblazer Project

- Focusing on Technologies to Enable Affordable Access to Space
- Integrating RBCC Propulsion into a Near-Term Demonstrator
  - SSTO VTOHL Configurations
  - Three Different Class Concepts
- Parallel Development of Vehicle and Propulsion Technologies
- Vying to Become an Integral Part of NASA Bantam Program
  - Concept Downselect in 2001
  - Flight Demo in 2007
- Five In-House Test Rigs in Work
  - Subscale Inlet
  - Ejector Rocket
  - Variable Mode Combustor
  - Vehicle Aerodynamics

NASA Langley Research Center



Hyper-X
NASA Langley Research Center 3/19/1997 Image # EL-1997-00031

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Airbreathing Launch Vehicle (ABLV) Study

- Study is sponsored by NASA MSFC's Advanced Reusable Technologies (ART) project
- Cooperative effort by NASA LaRC, Glenn, and MSFC to evaluate a matrix of. SSTO concepts for access to space missions
  - 8 HTOHL configurations
  - 4 VTOHL configurations
- Emphasis on RBCC & TBCC propulsion integration and vehicle design resolution
  - Design
  - Performance Analysis / Closure
  - Sensitivities

ABLV Addresses Advanced Propulsion Technology and Vehicle Integration challenges.

NASA Marshall Space Flight Center

ART is Establishing a Pipeline of Demonstrations that will Facilitate Future RBCC Engine Designs

Advanced Reusable Technologies (ART) Program

- NASA's Most Aggressive Pursuit of RBCC Engine Technology
- Four Engine Companies Selected (1996)
  - Aerojet
  - Kaiser Marquardt
  - Rocketdyne
  - Pratt & Whitney
- Additional Support Provided By:
  - Pennsylvania State (CFD)
  - Astrox Corp. (Flowpath Analysis)
- Several Subscale Engines Built and Tested at GASL, Focusing On:
  - Performance
  - Mode Transition
- Results Could Lead to Flight Demo.
  - Bantam
  - Future -X

Future Prospects

- Air Force and NASA recognize RBCC technology may be the key to affordable access to space.
- Today's engine technology programs are leveraging off of past accomplishments
  - Liquid rocket propulsion is the Foundation to the engine cycle
  - Ejector rocket are very Mature and have a large database
  - Liquid rocket technology advancements are directly applicable to RBCC
- There is a need to better understand overall engine performance
  - Identify performance margins
  - Increase design robustness
  - Build flight-type hardware
  - Characterize engine mode transition
- Many challenges are being addressed in current programs.

Future Prospects

- RBCC technology is rapidly approaching the limit of what can be accomplished through ground testing.
- The next step is the design, fabrication and testing of a flightweight propulsion system
  - Actively cooled composite structures
  - Flight-type propellant delivery system
  - Flight-type engine controls
- For military operations, there is a need for engine analysis and design using hydrocarbon fuels.
- RBCC technology holds the promise of routine access to space
  - Vehicle robustness
  - Increased payload mass fractions